UNDERSTANDING GLOBAL CLIMATE CHANGE WITH OCEAN ACOUSTIC TOMOGRAPHY AND MODELS

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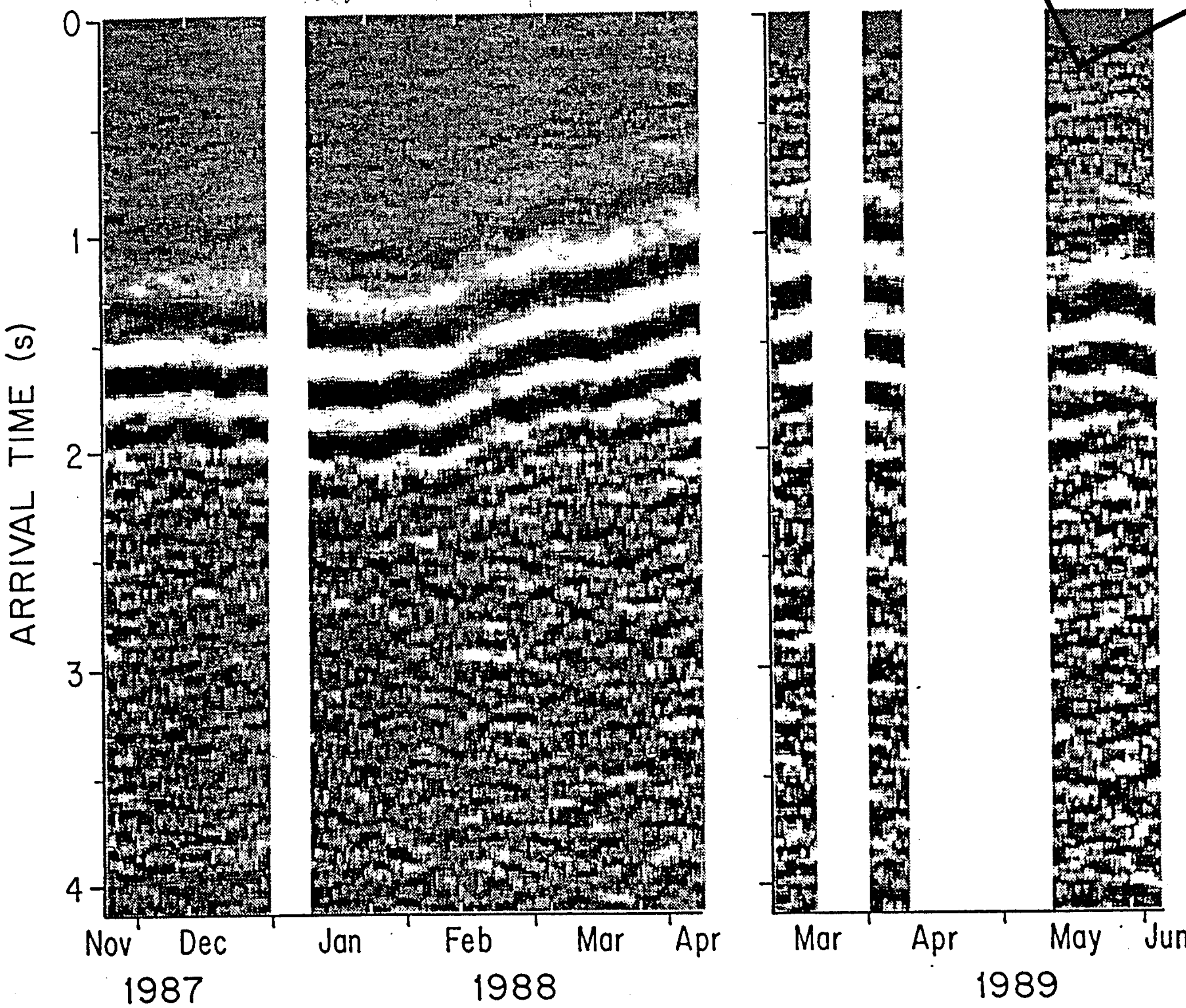

Basin-scale ocean acoustic thermometer. Changes in travel time (vertical axis) are indicated for the arrival times of acoustic pulses (black streaks) during the indicated months in 1987-1989. The pulses travel through the ocean between an underwater source near Hawaii and an underwater receiver near the coast of northern California. The decrease in travel time beginning in February 1988 indicates warming along the 4000 km section. Adapted from Spiesberger et al., 1992.

UNDERSTANDING GLOBAL CLIMATE CHANGE WITH OCEAN ACOUSTIC TOMOGRAPHY AND MODELS

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Paleoclimate inferred from the Vostok ice core provides tantalizing evidence that increases in atmospheric CO_2 are dynamically linked with increases in atmospheric temperature (Jouzel et al., 1987; Barnola et al., 1987; Genthon et al., 1987). However, the mechanisms responsible for the temporal and spatial scales of the accompanying temperature change are not understood because, in part, the ocean's role is not well understood. New technology is required to see inside the global oceans where vasts amount of heat are redistributed and eventually exchanged with the atmosphere. Waves and other features at large scales, $\sim$ 100 to 10,000 km, having time scales less than centuries are virtually unexplored but these scales are important for understanding climate change (Gill, 1982; Philander, 1990). We are developing novel acoustic instruments that have the potential for measuring these scales in the global oceans in real-time. The cost for these measurements is projected to be less than the costs of mapping temperature and other variables in the atmosphere (Spiesberger, 1992).

Background

At frequencies below a few hundred Hertz, sound is a natural probe of the ocean because it undergoes little absorption and because it is bent away from the surface and the bottom of the ocean where it would otherwise be scattered. Sound pulses travel to a distant receiver along many paths, called multipaths. The time of travel along each multipath in the sea is different, so many pulses are heard although only one is transmitted (Fig. 1). Munk and Wunsch (1979) suggested applying geophysical inverse techniques to map temperatures in the interior of the ocean from the travel times of acoustic pulses measured between sources and receivers submerged below the ocean's surface. These principals were successfully applied over 300 km distances to map the ocean mesoscale (Cornuelle et al., 1985; Howe et al., 1987).

Beginning in 1983, the travel times of sound were measured over basin-scales ($\sim$ 4000 km) in the northeast Pacific to detect hypothetical changes in climate related to global warming and other phenomenon (Spiesberger et al., 1992; Spiesberger and Metzger, 1992). To date, acoustic transmissions have been made through 1989 on an intermittent basis (Fig. 2).

Three criteria must be met in order to measure climatic changes of ocean temperature with sound: (1) sound must be detected; (2) acoustic multipaths must be tracked from day to day, over a period of years, to form a geophysical time series of travel time;

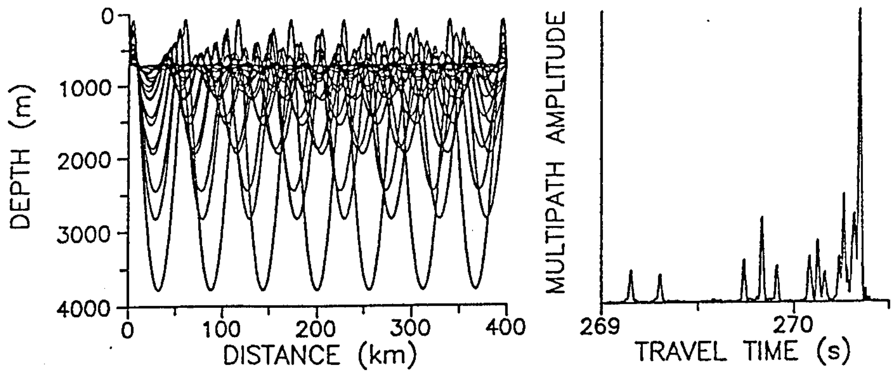

Fig. 1. Left: *The paths (multipaths) of acoustic waves emitted from an acoustic source at 700 m depth to an acoustic receiver at the same depth and at a distance of 400 km. Only paths that leave the source in an upgoing direction are shown.* **Right:** *The travel times of the multipaths. The steepest multipaths arrive first, and the flattest arrive last.*

(3) it must be shown that changes in acoustic travel time are caused by temperature changes, and not other physical variables such as currents, salinity, or pressure.

Spiesberger et al. (1992) found that all three criteria could be met. The transmitted signal was only as loud as that emitted by the mating call of a male finback whale (*Balaenoptera physalus*), ~ 183 dB, but was clearly detected at basin-scales following application of standard signal processing techniques. Acoustic multipaths could be tracked over periods of months to years (e.g. cover). Most importantly, changes in acoustic travel time were shown to be due to changes in the spatially averaged temperature between the source and the receivers. The acoustic thermometer was accurate enough to detect changes as small as 0.02° C. As temperature rises, the speed of sound increases and the travel time decreases. These measurements of travel time do not yet demonstrate any climatic trends which might be ascribed to greenhouse warming of the Pacific in the seven year period between 1983 and 1989. The travel time data do show less sensitivity to small scale temperature fluctuations than point measurements because the acoustic travel times are integral measurements. In this study, travel times were not converted to temperature using tomography. A simpler technique was used. Nevertheless, acoustic measures of temperature provide an orthogonal perspective by which temperatures in the ocean may be observed and eventually understood.

Acoustic tomography requires addition of a fourth criterion: the spatial coordinates of acoustic multipaths must be determined. Then, vertical maps of temperature can be made because of the differential way in which multipaths sample the vertical dimension. The fourth criterion has been demonstrated at basin-scales (Spiesberger and Metzger, 1991,1992). The practical nature of this technique was proven when the multipath coordinates were determined from historical data rather than from data obtained from costly ship surveys between the source and the receiver. Tomographic maps of the ocean's large-scale thermal field exhibit statistically significant trends in the layers from 0 to 100 m and from 100 to 300 m. Available data from satellites and point measurements are insufficient for detecting these trends.

Munk's recent Heard Island experiment transmitted electronically generated sounds half way around the earth (Munk and Forbes, 1989). What they showed was that

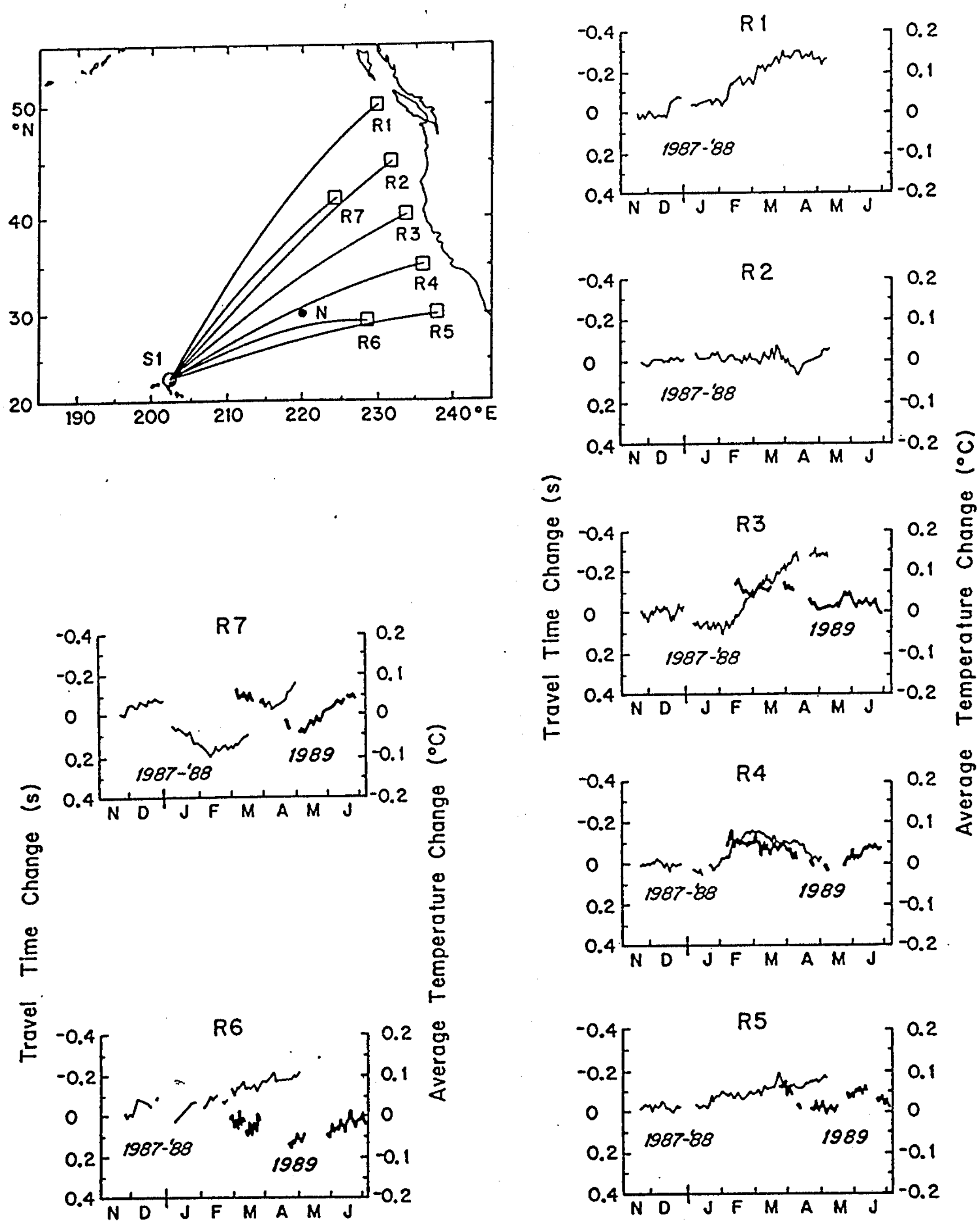

Fig. 2. **Upper left:** *Plan view of the initial global warming experiment with the approximate positions of the acoustic source (S1) and seven receivers (R1 to R7) indicated. The other panels tabulate the change in acoustic travel-time (reckoned to travel-time in November 1987) at each of the seven receivers up to June of 1989 except for receivers 1 and 2 for which no data exist in 1989. The right-hand axes provide an approximate guide (to within about 30%) as to how much the average temperature need change in the upper kilometer to yield changes in acoustic travel time. Adapted from Spiesberger and Metzger (1992).*

criterion (1) above could be met: sound was detected at semi-global distances. However, according to results presented to date, the multipath signals were not repeatable from hour to hour or from day to day. Repeatability is a pre-requisite for forming a multi-year time series of acoustic travel time for climatic temperature changes. There are still many puzzles to solve in underwater acoustics, including why these multipaths were not repeatable.

Ocean models

El niño is hypothesized to play an important role in changing acoustic travel times by ± 0.2 s in the northeast Pacific (Spiesberger et al., 1992)(Fig. 2). Following Shriver, Johnson, and O'Brien (1991), when the trades slacken at the onset of el niño, an equatorially trapped Kelvin wave propagates from the west Pacific to the coast of Ecuador in about two months. Poleward travelling Kelvin waves then propagate along the west coast of the Americas. Waters become unseasonably warm along the coast because the Kelvin waves depress the thermocline thus inhibiting the upwelling of cold water. Westward propagating Rossby waves (~ 1.5 cm s^{-1}, 1000 km wavelength, 2-4 yr period) are excited at the coasts, which depress the thermocline by hundreds of meters. The depression of the thermocline leads to warming in the upper layer by the same mechanism that leads to warming of coastal waters by the coastal Kelvin wave. After several years, these waves propagate thousands of kilometers into the northeast Pacific. Preliminary calculations indicate these Rossby waves can change acoustic travel times by 0.2 s and can lead to much of the striking variability seen from receiver-to-receiver (Fig. 2).

Shriver, Johnson, and O'Brien's (1991) model, mentioned above, and related models, are particularly well suited for investigating climate variability because (1) their physics is sufficient to understand realistic variability but not so complicated so that the behavior of the model is obscure, and (2) they are driven by observed monthly wind fields that are important in determining the circulation. We are adapting these models for interpreting and assimilating tomographic data such as that shown in Fig. 2.

Living Atlas of the Ocean

"My recent enthusiasm ... over the prospects of a living atlas, with oceanographic data displayed on the color screen of a microcomputer, has roots going back to the early 1960s" (Stommel, 1987). The question is how to sample the ocean's interior at large scales at an affordable cost. Our approach involves two new instruments; a Surface Suspended Acoustic Receiver (SSAR) and an autonomously moored subsurface mooring with an acoustic source. The novel aspect of the mooring is its telemetry capability permitting correction of tomographic travel times for mooring wander in real time (Spiesberger and Bowlin, 1992).

Interannual variability in temperature causes acoustic travel times to change by ± 0.2 s at basin-scales (Fig. 2). Thus, travel times need to be measured ten times better, ± 0.02 s, to detect these signals. Distance between the source and receiver must correspondingly be measured to within $\pm 0.02 \text{ s} \times 1500 \text{ m s}^{-1} = \pm 0.03$ m where the speed of sound in the sea is about 1500 m s^{-1}. Calculations indicate these accuracies can be met with the instruments described below (Spiesberger and Bowlin, 1992).

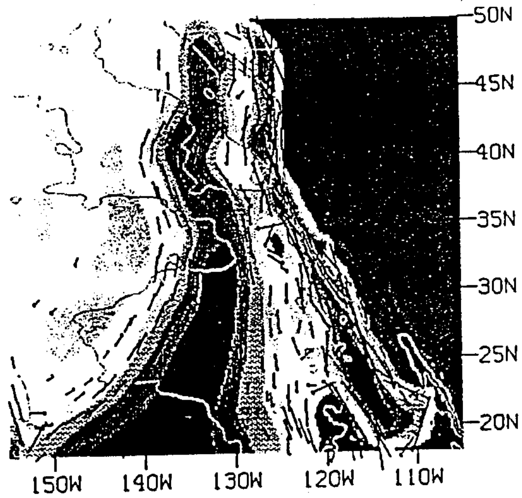

Fig. 3. Model for upper layer thickness anomalies due to westward propagating Rossby waves excited via oceanic teleconnections following an el niño. The Rossby wave between 150W and 130W (black swath) depresses the upper layer by about 250 m. Arrows indicate currents. Hawaii is in the lower left-hand corner and the U.S. continent is on the right. These Rossby waves are candidates for explaining the travel time variations shown in Fig. 2.

Surface Suspended Acoustic Receiver (SSAR)

The SSAR is propelled by winds and currents (left panel, Fig. 4). As it moves, it receives acoustic signals across a wide spatial aperture from each tomographic source. Like synthetic aperture radars, the synthetic aperture from a drifting SSAR provides images with higher spatial resolution than possible with a stationary receiver. The gain in spatial resolution is significant because the features responsible for climate change are typically large and slowly changing. It is desirable to make the cost of each SSAR as low as possible so they may be considered expendable.

Mooring and Telemetry

Tomographers have placed acoustic sources on standard subsurface moorings for more than a decade (right panel, Fig. 4). Because of currents, it is necessary to measure and correct for mooring wander of hundreds of meters that causes acoustic travel times to change by about ± 0.1 s. The correction problem is similar to the determination of an earthquake's epicenter from seismic records. In the past, the position of the mooring was estimated by measuring the two-way travel times of sound between an interrogator near the source and three or more transponders at known locations on the sea floor (Cornuelle et al., 1985). Corrections to the travel times have always been made after the mooring was recovered.

We suggest correcting for mooring wander in real-time by shifting the nominal start times of tomography transmissions in pre- determined ways (Spiesberger and Bowlin, 1992). An important feature of the new telemetry technique is that no extra battery energy is required over and above that used in conventional tomography experiments. Battery energy is a limiting factor in the lifetime and cost of these moorings.

The principle of this telemetry scheme can be understood by considering one source and one receiver. The source uses its local navigation system to estimate its location, then shifts its nominal transmission time so that the arrival time of the signal is though the source was at a nearby reference position. The reference position is determined before the experiment. A tomographic map can be made in real- time if the source is assumed to reside at the reference position. This principle can be generalized for many receivers, including rapidly drifting receivers where the source does not know their positions.

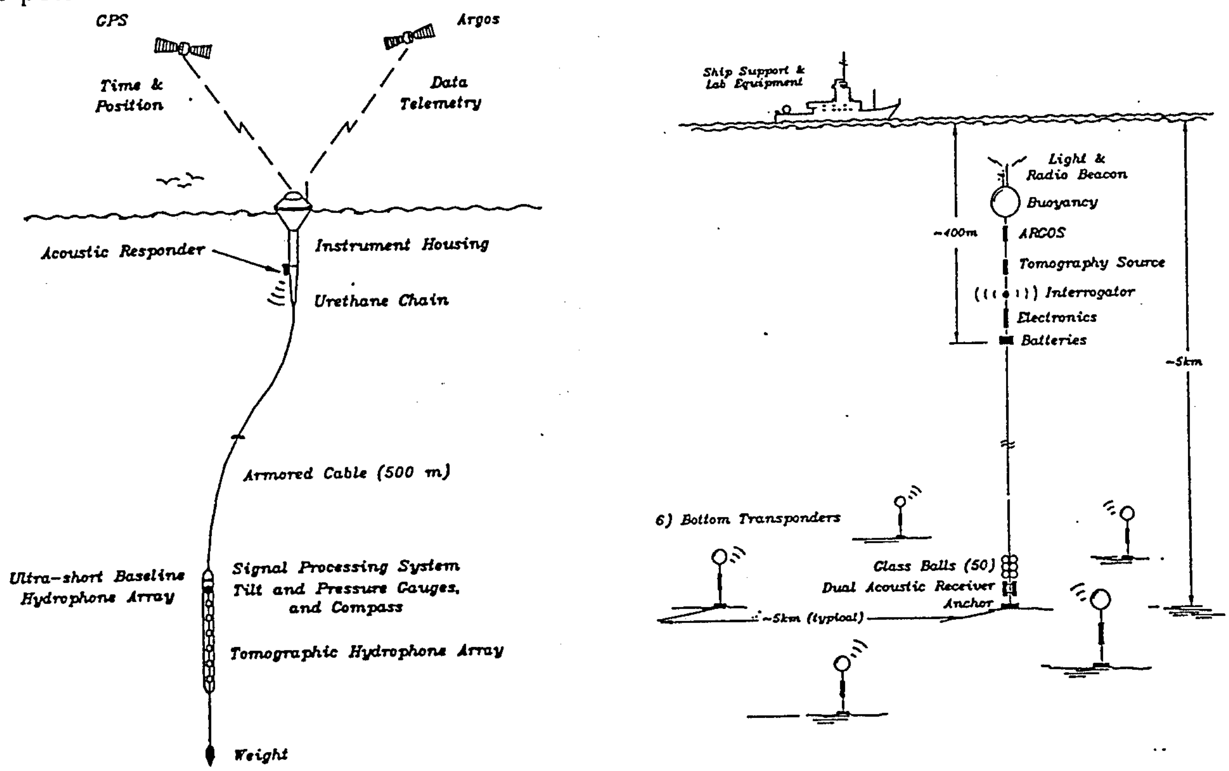

Fig. 4. Left: *Surface Suspended Acoustic Receiver (SSAR) transmits compressed tomography data to ARGOS satellites and receives position and timing information from the GPS satellites. Navigation of the subsurface hydrophone array is accomplished with an ultra-short baseline acoustic navigation system.* Right: *A subsurface mooring with an acoustic source and a local acoustic navigation system.*

Acoustic Source

Basin-scale monitoring from moorings can be done with a source level of about 197 dB re 1μPa @ 1m, a center frequency of about 200 Hz, an acoustic bandwidth of about 50 Hz, a corresponding pulse resolution of $\frac{1}{50\ Hz} = 0.02$ s, an efficiency of about 50%, a reliability of at least 3×10^7 cycles, and an operating depth of about 500 m (Spiesberger and Bowlin, 1992). The compact electromagnetic monopole source developed by Mark Slavinsky and Boris Bogolubov (Institute of Applied Physics of the Russian Academy of Sciences) exceeds most of these requirements except for operation at 500 m (Slavinsky et al., 1992). A new pressure compensation system is required for operation at 500 m.

Economics

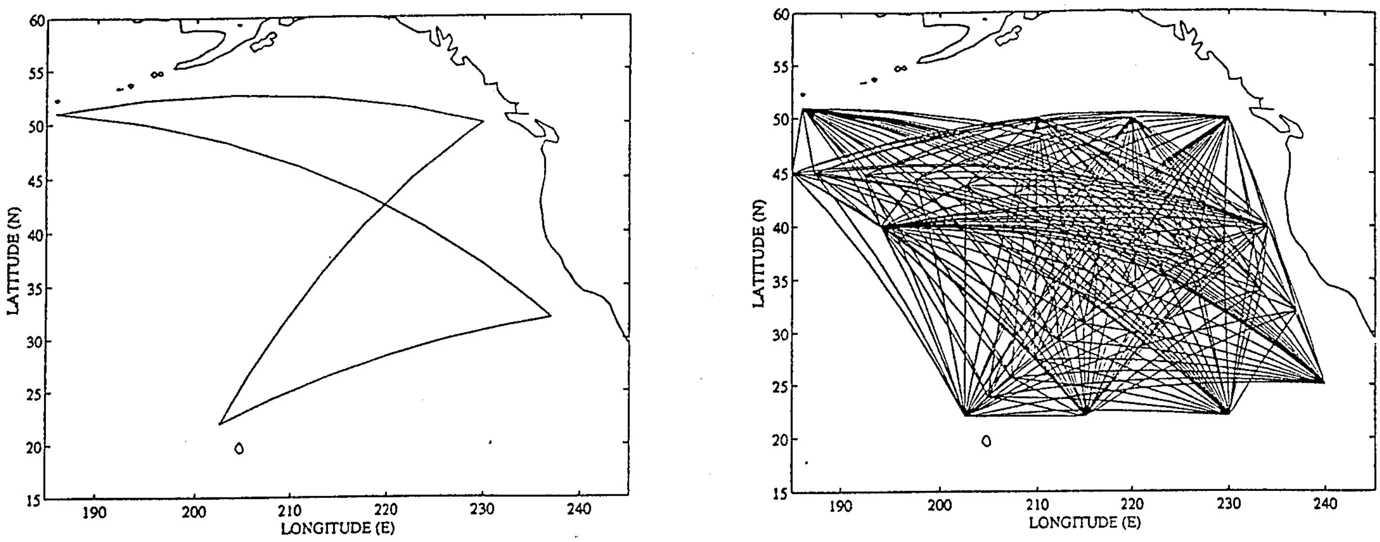

Fig. 5. Left: *The maximum tomographic coverage possible with cabled systems given $11 million over ten years. There are two sources and two receivers in the northeast Pacific. Hawaii is indicated at* 20° *N,* 205° *E.* Right: *The maximum tomographic coverage possible with new acoustic technology based on SSARs and autonomously moored sources given $10 million over ten years. There are ten moorings and twenty six SSARs. The resolution obtained thereby is better than 500 km, sufficient to resolve Rossby waves. These estimates assume the following costs: Cabled sources and receivers at $1.5 and $1 million each with maintenance costs of $0.17 and $0.12 million each per year respectively. Moored sources and SSARs at $0.162 and $0.025 million each with maintenance costs of $0.035 and $0.017 million each per year respectively. See Spiesberger (1992) for details.*

Economics is intimately related to any engineering solution to the problem of sampling the ocean's large interior scales at time scales less than a few centuries. Simple economic principles have been developed for acoustic tomography which allow us to calculate (1) how many sources and receivers to deploy to maximize the number of tomographic sections given a fixed budget and (2) the minimum cost for achieving a given spatial resolution (Spiesberger, 1992). We find that cabled sources and receivers are prohibitively expensive if Rossby wave resolution ($\sim$ 500 km) is desired in the global oceans. However, the cost of obtaining this resolution is affordable, and actually cheaper than monitoring the atmosphere, if tomographic systems are built from SSARs and moored sources (Fig. 5).

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